

EXTRACTING PREDICTIONS FROM SUPERGRAVITY/SUPERSTRING FOR THE EFFECTIVE THEORY BELOW THE PLANCK SCALE *

C. MUÑOZ

*Departamento de Física Teórica C-XI, Universidad Autónoma de Madrid, Cantoblanco
Madrid, E-28049, Spain*

ABSTRACT

The connection between Superstring theory and the low-energy world is analyzed. In particular, the soft Supersymmetry-breaking terms arising in Supergravity theories coming from Superstrings are computed. Several solutions proposed to solve the μ problem, and the B soft term associated, are discussed. The issue of gauge coupling constants unification in the context of Superstrings is also discussed.

FTUAM 95/5
March 1995

1. Introduction and Summary

The most outstanding virtue of Superstring theory is that it is the only (finite) theory which can unify all the known interactions including gravity. Furthermore, it is the only hope to answer fundamental questions that in the context of the Standard Model (SM) or Grand Unified Theories (GUTs) cannot even be posed: why the gauge and Yukawa couplings should have a particular value?. First, the gauge coupling constant is dynamical because it arises as the vacuum expectation value (VEV) of a gauge singlet field S called the dilaton, $\langle ReS \rangle = 1/g^2$. Second, the Yukawa couplings, which determine the quark and lepton masses, can be explicitly calculated and they turn out to be also dynamical. They depend in general on other gauge singlet fields T_m called the moduli whose VEV determine the size and shape of the compactified space. E.g. for the overall modulus $\langle ReT \rangle \sim R^2$. Of course, experimental data demand $ReS \sim 2$ and $ReT \sim 1$ (in Planck mass units). Therefore the initial questions translate as how are the VEV determined. This will be discussed below. Finally, it is possible to obtain models resembling the Supersymmetric Standard Model (SSM) at low-energy. Of course, this is crucial in order to connect Superstring theory with the observable world.

The particle spectrum in the SSM is in general determined by the soft Supersymmetry (SUSY)-breaking terms. In the simplest SSM, the so-called Minimal Supersymmetric Standard Model (MSSM), assuming certain universality of soft terms these can be parametrized by only four parameters: a universal gaugino mass M , a universal scalar mass m , a universal trilinear scalar parameter A and an extra bilinear scalar parameter B . These soft terms are very important not only because they

*Plenary talk given at the International Conference "Beyond the Standard Model IV", Lake Tahoe (California), December 13-18, 1994.

determine the SUSY spectrum, like gaugino, squark and slepton masses, but also because they contribute to the Higgs potential generating the radiative breakdown of the electroweak symmetry.

When Supergravity (SUGRA) is spontaneously broken in a "hidden sector" the soft SUSY-breaking terms are generated. These are characterized by the gravitino mass ($m_{3/2}$) scale and therefore in order not to introduce a problem of naturalness, $m_{3/2}$ should be of the electroweak scale order (recall that the soft terms contribute to the Higgs masses). An interesting non-perturbative source of SUSY-breaking, capable of generating this large mass hierarchy, is gaugino condensation in some hidden sector gauge group.

The full SUGRA Lagrangian is specified in terms of two functions which depend on the hidden and observable scalars of the theory: the real analytic gauge-invariant Kähler function G which is a combination of two functions K (the Kähler potential) and W (the superpotential), and the analytic gauge kinetic function f . Then, once we know these functions the soft SUSY-breaking terms are calculable. For example, for the simple case of canonical kinetic terms for hidden and observable fields and constant f , it is straightforward to compute the form of the soft terms¹

$$\begin{aligned} M &= 0 \\ m^2 &= m_{3/2}^2 + V_0 \\ A &= m_{3/2} \sum_l h_l^* G_{h_l} \\ B &= A - m_{3/2} \end{aligned} \tag{1}$$

where h_l are the hidden sector fields, V_0 is the VEV of the scalar potential (i.e. the cosmological constant), and we use standard SUGRA conventions on derivatives (e.g. $G_\alpha = \frac{\partial G}{\partial z_\alpha}$, $G^\alpha = \frac{\partial G}{\partial z_\alpha}$). $M = 0$ is a consequence of the assumption that f is a constant.

Unfortunately for the predictivity of the theory, G and f are arbitrary and therefore the soft terms become SUGRA model dependent. Besides, the existence of the "hidden sector" has to be postulated "ad hoc". All these problems can be solved in Superstring theory.

In particular, the Heterotic Superstring after compactification of six extra dimensions (on some compact manifolds) leads to a $N = 1$ effective SUGRA. Now, K and f are *in principle calculable* from Superstring scattering amplitudes. Besides, whereas in SUGRA (non-Superstring) models we do not have the slightest idea of what fields could be involved in SUSY-breaking, four-dimensional *Superstring theory automatically has natural candidates for that job*: the dilaton S and the moduli T_m . These gauge singlet fields are generically present in four-dimensional Heterotic Superstring since S is related with the gravitational sector of the theory and T_m are related with the extra dimensions. While other extra fields could also play a role in specific models, the dilaton and moduli constitute in some way the *minimal possible SUSY-breaking sector in Superstring theory*[†]

[†]Starting with this minimal sector one can also study the possible role on SUSY-breaking of other extra fields (see the example discussed in section 8 of ref.²).

Concerning the superpotential W , the situation is more involved. It is known that the process of SUSY-breaking in Superstring theory has to have a non-perturbative origin since SUSY is preserved order by order in perturbation theory (the scalar potential $V(S, T_m)$ is flat) and hence S and T_m are undetermined at this level. On the other hand, very little is known about non-perturbative effects in Superstring theory, particularly in the four-dimensional case. It is true that gaugino condensation gives rise to an effective W which breaks SUSY at the same time that S and T_m acquire reasonable VEVs³ (as the ones explained above), and determines explicitly the values of the soft SUSY-breaking terms⁴. However one should keep in mind that this analysis requires the assumption that the dominant non-perturbative effects in Superstring theory are the field theory ones. This is because gaugino condensation is not a pure "stringy" mechanism. Thus a pessimist would say that Superstring theory does not look particularly promising in trying to get information about the SUSY-breaking sector of the theory.

However, since K and f are known, and the degrees of freedom involved in the process of SUSY-breaking have been identified (the "hidden fields" S and T_m), the effect of SUSY-breaking can be parametrized by the VEVs of those fields. In the next section we review this approach for addressing the problem, trying to provide a theory of soft terms which could enable us to interpret the (future) experimental results on SUSY spectra. It turns out to be specially useful to introduce several "goldstino angles" whose values tell us where the dominant source of SUSY-breaking resides. All formulae for soft parameters take on particularly simple forms when written in terms of these variables. In section 3 a different kind of connection between Superstring theory and the low-energy phenomenology is analyzed, namely the possibility of obtaining the gauge coupling constants unification in Superstring models as the experimental (LEP) results demand.

2. Soft terms from Superstring theory

2.1. General structure of soft terms

K (to first order in the observable fields ϕ_i) is given in general by the form

$$K = -\log(S + S^*) + K_0(T, T^*) + K_{ij}(T, T^*)\phi_i\phi_j^* \quad (2)$$

where the indices i, j label the charged matter fields[†]. Amongst the moduli T_m we concentrate, for the moment, on the overall modulus T whose classical value gives the size of the manifold. Apart from simplicity, this modulus is the only one which is always necessarily present in any (0, 2) (but left-right symmetric) 4-D Superstrings. We believe that studying the one modulus case is enough to get a feeling of the

[†]For phenomenological reasons related to the absence of flavour changing neutral currents (FCNC) in the effective low-energy theory (see section 5 of ref.² for a discussion of this point) from now on we will assume a diagonal form for the part of the Kähler potential associated with matter fields, $K_{ij} = K_i\delta_j^i$ in eq.(2).

most important physics of soft terms. Anyway, the case with several moduli will be analyzed in subsection 2.4. We will disregard for the moment any mixing between the S and T fields kinetic terms. In fact this is strictly correct in all 4-D Superstrings at tree level. However, it is known that this type of mixing may arise at one loop level in some cases. On the other hand, these are loop effects which should be small and in fact can be easily incorporated in the analysis in some simple cases (orbifolds) as mention below.

The tree-level expression for f for any four-dimensional Superstring is well known, $f_a = k_a S$, where k_a is the Kac-Moody level of the gauge factor. Normally (level one case) one takes $k_3 = k_2 = \frac{3}{5}k_1 = 1$. Since a possible T dependence may appear at one-loop (higher-loop corrections are vanishing), then in general

$$f_a(S, T) = k_a S + f_a(T) \quad (3)$$

where we assume that other possible chiral fields do not contribute to SUSY-breaking.

Finally, the cosmological constant is

$$V_0 = G_S^S |F^S|^2 + G_T^T |F^T|^2 - 3e^G \quad (4)$$

Of course, the first two terms in the right hand side of eq.(4) represent the contributions of the S and T auxiliary fields, $F^S = e^{G/2}(G_S^S)^{-1}G^S$ and $F^T = e^{G/2}(G_T^T)^{-1}G^T$.

As we will show below, it is important to know what field, either S or T , plays the predominant role in the process of SUSY-breaking. This will have relevant consequences in determining the pattern of soft terms, and therefore the spectrum of physical particles. That is why it is very useful to define an angle θ in the following way² (consistently with eq.(4)):

$$\begin{aligned} (G_S^S)^{1/2} F^S &= \sqrt{3}C m_{3/2} e^{i\alpha_S} \sin\theta \\ (G_T^T)^{1/2} F^T &= \sqrt{3}C m_{3/2} e^{i\alpha_T} \cos\theta \end{aligned} \quad (5)$$

where α_S, α_T are the phases of F^S and F^T , and the constant C is defined as follows:

$$C^2 = 1 + \frac{V_0}{3m_{3/2}^2} \quad (6)$$

If the cosmological constant V_0 is assumed to vanish, one has $C = 1$, but we prefer for the moment to leave it undetermined. Of course, the way one deals with the cosmological constant problem is important.

Notice that, with the above assumptions, the goldstino field which is swallowed by the gravitino in the process of SUSY-breaking is proportional to

$$\tilde{\eta} = \sin\theta \tilde{S} + \cos\theta \tilde{T} \quad (7)$$

where \tilde{S} and \tilde{T} are the canonically normalized fermionic partners of the scalar fields S and T (we have reabsorbed here the phases by redefinitions of the fermions \tilde{S}, \tilde{T}).

Thus the angle defined above may be appropriately termed *goldstino angle* and has a clear physical interpretation as a mixing angle.

Then it is straightforward to compute the general form of the soft terms²

$$M_a = \frac{C\sqrt{3}}{2\text{Ref}_a} m_{3/2} (k_a 2\text{Re}S e^{-i\alpha_S} \sin\theta + f_a^T (G_{0T}^T)^{-1/2} e^{-i\alpha_T} \cos\theta) \quad (8)$$

$$m_i^2 = 2m_{3/2}^2 (C^2 - 1) + m_{3/2}^2 C^2 (1 + N_i(T, T^*) \cos^2\theta)$$

$$N_i(T, T^*) = \frac{3}{K_{0T}^T} \left(\frac{K_{iT} K_i^T}{K_i^2} - \frac{K_{iT}^T}{K_i} \right) = -3 \frac{(\log K_i)_T^T}{K_{0T}^T} \quad (9)$$

$$A_{ijk} = -\sqrt{3} m_{3/2} C (e^{-i\alpha_S} \sin\theta + e^{-i\alpha_T} \omega_{ijk}(T, T^*) \cos\theta)$$

$$\omega_{ijk}(T, T^*) = (K_{0T}^T)^{-1/2} \left(\sum_{l=i,j,k} \frac{K_l^T}{K_l} - K_0^T - \frac{Y_{ijk}^T}{Y_{ijk}} \right) \quad (10)$$

$$\begin{aligned} B_\mu &= m_{3/2} (-1 - C\sqrt{3} e^{-i\alpha_S} \sin\theta (1 - \frac{\mu^S}{\mu} (S + S^*))) \\ &+ C\sqrt{3} e^{-i\alpha_T} \cos\theta (K_{0T}^T)^{-1/2} (K_0^T + \frac{\mu^T}{\mu} - \frac{K_{H_1}^T}{K_{H_1}} - \frac{K_{H_2}^T}{K_{H_2}}) \end{aligned} \quad (11)$$

where Y_{ijk} are the usual Yukawa couplings. The above expressions become much simpler in specific four-dimensional Superstrings and/or in the large- T limit. This is the case for instance of the formula for $N_i(T, T^*)$ which looks complicated but it becomes very simple. N_i is related to the curvature of the Kähler manifold parametrized by the above Kähler potential. For manifolds of constant curvature (like in the orbifold case) the N_i are constants, independent of T . More precisely, they correspond to the modular weights of the charged fields, which are normally negative integer numbers. In more complicated four-dimensional Superstrings like those based on Calabi-Yau manifolds, the $N_i(T, T^*)$ functions are complicated expressions in which world-sheet instanton effects play an important role. In the case of $(2, 2)$ Calabi-Yau manifolds, for the large T limit it turns out that $N_i(T, T^*) \rightarrow -1$.

Anyway, the explicit dependence of the soft masses on the N_i of each particle produces a lack of universality^{5,4}. This may be relevant for the issue of flavour-changing neutral currents (FCNC). For an extended discussion on this point see section 5 of ref.² and refs.^{6,7}.

The soft terms obtained in the previous analysis are in general complex. Notice that if S and T fields acquire complex vacuum expectation values, then the phases α_S, α_T associated with their auxiliary fields can be non-vanishing and the functions $\omega_{ijk}(T, T^*)$, $f_a(T)$, etc. can be complex. The analysis of this situation in connection with the experimental limits on the electric dipole moment of the neutron (EDMN) can be found in refs.^{2,8}.

Finally, the above analysis has shown that the different soft SUSY-breaking terms have all an explicit dependence on V_0 , i.e. the cosmological constant, which is contained in C . We have to face this fact and do something about it[§]. We cannot just

[§]It is worth noticing that general properties which are independent of the value of the cosmological

simply ignore it, as it is often done, since the way we deal with the cosmological constant problem has a bearing on measurable quantities like scalar and gaugino masses. For an extended discussion on this point see sections 6 and 8 of ref.² and refs.^{9,10,11}.

The value of the B soft term depends on the solution proposed to generate a μ term in the low-energy theory. In ref.¹² was pointed out that the presence of a non-renormalizable term in the superpotential

$$\lambda W H_1 H_2 \quad (12)$$

characterized by the coupling λ , which mixes the observable sector with the hidden sector, yields dynamically a μ parameter when W acquires a VEV

$$\mu = \lambda W \quad (13)$$

The fact that μ is of the electroweak scale order is a consequence of our assumption of a correct SUSY-breaking scale $m_{3/2} = e^{K/2}|W| = O(M_W)$.

The superpotential eq.(12) which provides a possible solution to the μ problem can be naturally obtained in the context of Superstring theory. In ref.¹² a realistic example where non-perturbative SUSY-breaking mechanisms like gaugino-squark condensation induce superpotentials of the type eq.(12) was given. In ref.¹³ the same kind of superpotential was obtained using pure gaugino condensation. It was used the fact that in some classes of four-dimensional Superstrings (orbifolds) a possible $H_1 H_2$ dependence may appear in f at one-loop. In both cases $\lambda = \lambda(T)$ in general, so with this solution to the μ problem eq.(11) gives¹⁴ (let us call B_λ the B -term associated with eqs.(12,13))

$$B_\lambda = m_{3/2} \left((3C^2 - 1) + C\sqrt{3}e^{-i\alpha_T} \cos\theta (K_{0T}^T)^{-1/2} \left(\frac{\lambda^T}{\lambda} - \frac{K_{H_1}^T}{K_{H_1}} - \frac{K_{H_2}^T}{K_{H_2}} \right) \right) \quad (14)$$

The alternative mechanism in which there is an extra term in the Kähler potential

$$\delta K = Z H_1 H_2 + h.c. \quad (15)$$

originating a μ -term^{15,12} is also naturally present in some large classes of four-dimensional Superstrings. Then, the B -term (we will call it B_Z) is given by²

$$\begin{aligned} B_Z &= \frac{m_{3/2}}{X} \left((3C^2 - 1) + C\sqrt{3}e^{-i\alpha_T} \cos\theta (K_{0T}^T)^{-1/2} \left(\frac{Z^T}{Z} - \frac{K_{H_1}^T}{K_{H_1}} - \frac{K_{H_2}^T}{K_{H_2}} \right) \right. \\ &\quad \left. - C\sqrt{3}e^{i\alpha_T} \cos\theta (K_{0T}^T)^{-1/2} \frac{Z_T}{Z} + C^2 3 (K_{0T}^T)^{-1} \cos^2\theta \left(\frac{Z_T}{Z} \left(\frac{K_{H_1}^T}{K_{H_1}} + \frac{K_{H_2}^T}{K_{H_2}} \right) - \frac{Z_T^T}{Z} \right) \right) \\ X &\equiv 1 - C\sqrt{3}e^{i\alpha_T} \cos\theta (K_{0T}^T)^{-1/2} \frac{Z_T}{Z} \end{aligned} \quad (16)$$

constant can still be found (see subsection 3.3 of ref.²).

Indeed, in the case of some orbifold models and the large- T limit of Calabi-Yau compactifications one expect^{16,17,13}

$$Z \simeq \frac{1}{T + T^*} \quad (17)$$

Notice that it is conceivable that both mechanisms could be present simultaneously. In that case the general expresions for the B -term and Higgsino mass $\hat{\mu}$ are easily obtained¹⁴

$$B = \frac{1}{\hat{\mu}} (B_\lambda m_{3/2} \lambda + B_Z m_{3/2} X Z) (K_{H_1} K_{H_2})^{-1/2} \quad (18)$$

$$\hat{\mu} = (m_{3/2} \lambda + m_{3/2} X Z) (K_{H_1} K_{H_2})^{-1/2} \quad (19)$$

where B_λ and B_Z , X are given in eqs.(14) and (16) respectively.

2.2. The $\sin\theta = 1$ (dilaton-dominated) limit

Before going into specific classes of String models, it is worth studying the interesting limit $\sin\theta = 1$, corresponding to the case where the dilaton sector is the source of all the SUSY-breaking^{16,2} (see eq.(5)). Since the dilaton couples in a universal manner to all particles, this limit is quite model independent. Using eqs.(8–11,14,16) one finds the following simple expressions for the soft terms:

$$\begin{aligned} M_a &= \sqrt{3} C m_{3/2} \frac{k_a \text{Re} S}{\text{Re} f_a} e^{-i\alpha_S} \\ m_i^2 &= C^2 m_{3/2}^2 + 2 m_{3/2}^2 (C^2 - 1) \\ A_{ijk} &= -\sqrt{3} C m_{3/2} e^{-i\alpha_S} \\ B_\mu &= m_{3/2} (-1 - \sqrt{3} C e^{-i\alpha_S} (1 - \frac{\mu^S}{\mu} (S + S^*))) \\ B_\lambda &= B_Z = m_{3/2} (3C^2 - 1) \end{aligned} \quad (20)$$

Notice that the scalar masses and the A -terms are universal, whereas the gaugino masses may be slightly non-universal since non-negligible threshold effects might be present. It is obvious that this limit $\sin\theta = 1$ is quite predictive. For a vanishing cosmological constant (i.e. $C = 1$), the soft terms are in the ratio $m_i : M_a : A = 1 : \sqrt{3} : -\sqrt{3}$ up to small threshold effect corrections (and neglecting phases). This will result in definite patterns for the low-energy particle spectra^{18,2}.

2.3. Computing soft terms in specific Superstring models

In order to obtain more concrete expressions for the soft terms one has to compute the functions $N_i(T, T^*)$, $\omega_{ijk}(T, T^*)$ and $f_a(S, T)$. In order to evaluate these functions one needs a minimum of information about the Kähler potential K , the structure of

Yukawa couplings $Y_{ijk}(T)$ and the one-loop threshold corrections $f_a(T)$. This type of information is only known for some classes of four-dimensional Superstrings which deserve special attention. An extended study of two large classes of models, the large- T limit of Calabi-Yau compactifications and orbifold compactifications, can be found in ref.². The one-loop (Superstring) corrections to the Kähler potential in orbifolds, which mix S and T fields and as a consequence modify the tree-level soft terms, are also analyzed. The general pattern of SUSY-spectra found (assuming vanishing[¶] cosmological constant) is very characteristic.

2.4. Computing soft terms in the case with several moduli (T_m)

In the case with several moduli (T_m) the situation is more cumbersome and one is forced to define new goldstino angles. This was first done in section 8 of ref.² in a different context (extra matter fields). Following this line, eq.(5) is modified to^{19,20}

$$\begin{aligned} (G_S^S)^{1/2} F^S &= \sqrt{3} C m_{3/2} e^{i\alpha_S} \sin\theta \\ (G_{T_m}^{T_m})^{1/2} F^{T_m} &= \sqrt{3} C m_{3/2} e^{i\alpha_{T_m}} \cos\theta \Delta_m \end{aligned} \quad (21)$$

For instead, for $m = 4$ (this is e.g. the case of some Z_N and $Z_N \times Z_M$ orbifolds with three diagonal (1,1) moduli and one (2,1) moduli), three new goldstino angles are necessary: $\Delta_1 = \cos\theta_1$, $\Delta_2 = \sin\theta_1 \cos\theta_2$, $\Delta_3 = \sin\theta_1 \sin\theta_2 \cos\theta_3$, $\Delta_4 = \sin\theta_1 \sin\theta_2 \sin\theta_3$. Now, with these definitions, the computation of the soft terms gives

$$\begin{aligned} M_a &= \sqrt{3} m_{3/2} C \left(\frac{k_a \text{Re} S}{\text{Re} f_a} e^{-i\alpha_S} \sin\theta + \cos\theta \sum_m e^{-i\alpha_{T_m}} \frac{b_a^m (T_m + T_m^*) \hat{G}_2(T_m, T_m^*)}{32\pi^3 \text{Re} f_a} \Delta_m \right) \\ m_i^2 &= m_{3/2}^2 C^2 (1 + 3\cos^2\theta \sum_m n_i^m \Delta_m^2) + 2m_{3/2}^2 (C^2 - 1) \\ A_{ijk} &= -\sqrt{3} C m_{3/2} (e^{-i\alpha_S} \sin\theta + \cos\theta \sum_m e^{-i\alpha_{T_m}} \Delta_m \omega_{ijk}(T_m)) \\ \omega_{ijk}(T_m) &= 1 + n_i^m + n_j^m + n_k^m - (T_m + T_m^*) \frac{Y_{ijk}^{T_m}}{Y_{ijk}} \end{aligned} \quad (22)$$

where n_i are the modular weights of the matter fields. A more complete analysis including the B-term, one-loop (Superstring) corrections, phenomenological consequences, and a comparison with the overall modulus (T) case can be found in ref.¹⁴.

3. Gauge coupling constants unification in Superstring models

The experimental (LEP) results agree with the joining of the three gauge coupling constants of the MSSM at a single unification scale ($\sim 10^{16} \text{GeV}$). In Superstring

[¶]The impact of a non-vanishing tree-level cosmological constant on SUSY-spectra was studied in ref.¹⁰.

theory the coupling constants are unified even in the absence of a GUT^{||} since $ReS = 1/(k_a g_a^2)$. However, this unification takes place at a scale ($\sim 10^{17} GeV$), i.e. one order or magnitude of difference. Perhaps, to worry about a discrepancy ~ 10 when we are working with energy scales $\sim 10^{16}$ is nonsense. Anyway, three possible mechanisms have been proposed in order to explain this discrepancy in the context of the MSSM from Superstrings.

First, the normalization factor of the hypercharge (k_1) which is fixed in usual GUTs (e.g. $k_1 = 5/3$ in $SU(5)$), is a model-dependent number in Superstring models. Playing around with this number we could obtain the correct Weinberg angle and α_S (taking into account the experimental uncertainties) at low-energy. This mechanism was first proposed in ref.²¹ and analyzed in detail in ref.²². Second, large Superstring threshold effects could produce different values of the coupling constants at the Superstring unification scale but the same ones^{23,5} at a scale $\sim 10^{16} GeV$. Finally, one can consider further charged particles²⁴ apart from those of the MSSM. This will require the introduction of some intermediate mass scale(s).

In the context of Superstring GUTs the only possibility would be to have an intermediate scale $\sim 10^{16} GeV$ at which a GUT symmetry like $SU(5)$ or $SO(10)$ is at work.

4. References

1. R. Barbieri, S. Ferrara and C.A. Savoy, *Phys. Lett. Phys. Lett.* **119B** (1982) 343; L. Hall, J. Lykken and S. Weinberg, *Phys. Rev.* **D27** (1983) 2359.
2. A. Brignole, L.E. Ibáñez and C. Muñoz, *Nucl. Phys.* **B422** (1994) 125.
3. See e.g.: B. de Carlos, J.A. Casas and C. Muñoz, *Nucl. Phys.* **B399** (1993) 623, and references therein.
4. B. de Carlos, J.A. Casas and C. Muñoz, *Phys. Lett.* **B299** (1993) 234.
5. L.E. Ibáñez and D. Lust, *Nucl. Phys.* **B382** (1992) 305.
6. D. Choudhury, F. Eberlein, A. Köning, J. Louis and S. Pokorski, MPI-Ph/94-51.
7. J. Louis and Y. Nir, LMU-TPW 94-17.
8. K. Choi, *Phys. Rev. Lett.* **72** (1994) 1592.
9. K. Choi, J.E. Kim and H.P. Nilles, *Phys. Rev. Lett.* **73** (1994) 1758.
10. K. Choi, J.E. Kim and G.T. Park, SNUTP 94-94.
11. S. Ferrara, C. Kounnas and F. Zwirner, *Nucl. Phys.* **B249** (1994) 589 and erratum **B433** (1995) 255.
12. J.A. Casas and C. Muñoz, *Phys. Lett.* **B306** (1993) 288.
13. I. Antoniadis, E. Gava, K. Narain and T. Taylor, *Nucl. Phys.* **B432** (1994) 187.
14. A. Brignole, L.E. Ibáñez, C. Muñoz and C. Scheich, in preparation.

^{||}Thus GUT gauge groups, as e.g. $SU(5)$ or $SO(10)$, are not mandatory in order to have unification in the context of Superstring theory.

15. G.F. Giudice and A. Masiero, *Phys. Lett.* **B206** (1988) 480.
16. V. Kaplunovsky and J. Louis *Phys. Lett.* **B306** (1993) 269.
17. G. Lopes-Cardoso, D. Lüst and T. Mohaupt, *Nucl. Phys.* **B432** (1994) 68.
18. R. Barbieri, J. Louis and M. Moretti, *Phys. Lett.* **B312** (1993) 451.
19. A. Brignole, L.E. Ibáñez and C. Muñoz, unpublished (1993).
20. T. Kobayashi, D. Suematsu, K. Yamada and Y. Yamagishi, Kanazawa-94-16.
21. J.A. Casas and C. Muñoz, *Phys. Lett.* **B214** (1988) 543.
22. L.E. Ibáñez, *Phys. Lett.* **B318** (1993) 73.
23. L.E. Ibáñez and D. Lüst, G.G. Ross *Phys. Lett.* **B272** (1991) 251.
24. I. Antoniadis, J.E. Ellis, S. Kelley and D.V. Nanopoulos, *Phys. Lett.* **B271** (1991) 31.